



## Mechanistic variances in NO release: *ortho* vs. *meta* isomers of nitrophenol and nitroaniline†

 Cite this: *Chem. Commun.*, 2024, 60, 5431

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 Received 1st April 2024,  
Accepted 22nd April 2024

DOI: 10.1039/d4cc01497a

rsc.li/chemcomm

The NO release following 266 nm photolysis of *ortho* and *meta* isomers of nitrophenol and nitroaniline shows a bimodal translational energy distribution, wherein the slow and fast components originate from dynamics in the  $S_0$  and  $T_1$  states, respectively. The translational energy distribution profiles for any NO product state show a higher slow-to-fast (s/f) branching ratio for the *ortho* isomer in comparison with the *meta* isomer. The observed variation in the s/f branching ratio *vis-à-vis* the *ortho* and *meta* isomers is attributed to the presence of intramolecular hydrogen bonding between the *ortho* substituent and  $\text{NO}_2$  moiety, which favours the roaming mechanism.

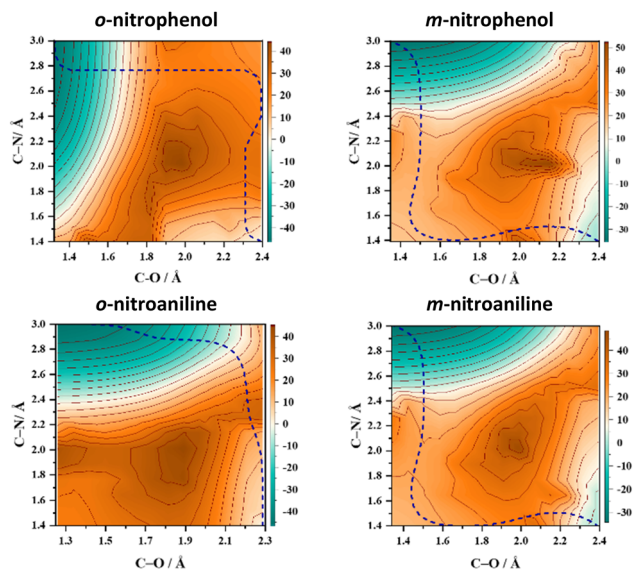
Nitroaromatic compounds produce nitric oxide (NO) upon irradiation, which modulates the oxidative capacity of the atmosphere.<sup>1,2</sup> Measurements on the translational energy distribution of NO fragments following UV photolysis of nitroaromatic compounds show the presence of slow and fast components (a bimodal behaviour), which has been interpreted as the presence of two distinct pathways for NO release.<sup>3,4</sup> The absence of a direct route to produce NO from nitroaromatic compounds suggests that both pathways must proceed *via* nitro-to-nitrite photoisomerization. The 266 nm excitation of nitrobenzene to high-lying electronic states ( $S_4/S_3$ ) results in ultrafast relaxation to the  $T_1$  state with a timescale of about 200 fs, and thereafter the dynamics on the  $T_1$  surface is much slower with the lifetime of about 90 ps, wherein the nuclear dynamics will dominate.<sup>5</sup> These observations are in accordance with the hypothesis that the topography of the  $T_1$  surface influences the dynamics of NO formation.<sup>3</sup> Based on electronic structure calculations, the fast NO component is attributed to a direct elimination channel from the  $T_1$  state featuring an oxaziridine ring-type (tight) transition state.<sup>3,4,6</sup> On the other hand, the slow translational energy component of the NO

radical is attributed to nitro-to-nitrite photoisomerization in the ground state, either arising from an oxaziridine ring-type and/or a  $\text{NO}_2$  roaming transition state. The  $\text{NO}_2$  roaming mechanism originates from the frustrated dissociation of the C–N bond in nitrobenzene and the  $\text{NO}_2$  radical is trapped in a shallow potential well around the phenyl radical and “roams” to form phenyl nitrite ( $\text{C}_6\text{H}_5\text{ONO}$ ), and the release of NO radical with low translational energy is attributed to the presence of an exit barrier for O–NO bond dissociation.<sup>4</sup> Thus far, it has been inferred that the slow translational energy component of the NO radical originates from the  $S_0$  state with both roaming and non-roaming (oxaziridine ring-type) mechanisms. Recent high-level electronic structure calculations have suggested that the topography of the  $T_1/S_0$  crossing points influences the slow and fast translational energy components of NO, which could involve oxaziridine or roaming-type geometries, and the roaming pathway has a relatively higher (4.61 eV) barrier.<sup>7</sup>

The ability of  $T_1$  surface topography to direct the NO release *via* the oxaziridine or roaming-type mechanisms, and thereby influence the relative yields of the fast and slow translational energy components, was investigated in several *ortho*-substituted nitrobenzenes by probing a specific NO fragment ( $\nu = 1; J = 50.5$ ) state.<sup>8</sup> In these cases the appearance of the bimodal translation energy distribution profile of the NO radical was dependent on the nature of the substituent. The substituents that were capable of forming intramolecular hydrogen bonding with the  $\text{NO}_2$  group, such as OH and  $\text{NH}_2$  groups, favoured the slow component over the fast component. In other words, the slow-to-fast (s/f) branching ratio between the components of the total translation energy distribution profile of NO was greater than one ( $s/f > 1$ ) in the case of *o*-nitrophenol and *o*-nitroaniline. On the other hand, a reverse trend with  $s/f < 1$  was observed for *o*-nitroanisole and *o*-nitrotoluene, wherein the substituents do not hydrogen bond with  $\text{NO}_2$ . The experimentally observed results were interpreted on the basis of two-dimensional potential energy surfaces (2D-PESs) in the  $T_1$  state and it was inferred that the minimum energy path favours the  $\text{NO}_2$  roaming mechanism for the

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† Electronic supplementary information (ESI) available: Methodology, 2D-PES at the M0-62X/6-311++G (d,p) level, one dimensional cut of the  $T_1$ -2D-PES along the MEP of NO release, VMI images and fitting of the  $[P(E_T)]$  profiles, and  $T_1/S_0$  crossing in nitroaniline. See DOI: <https://doi.org/10.1039/d4cc01497a>

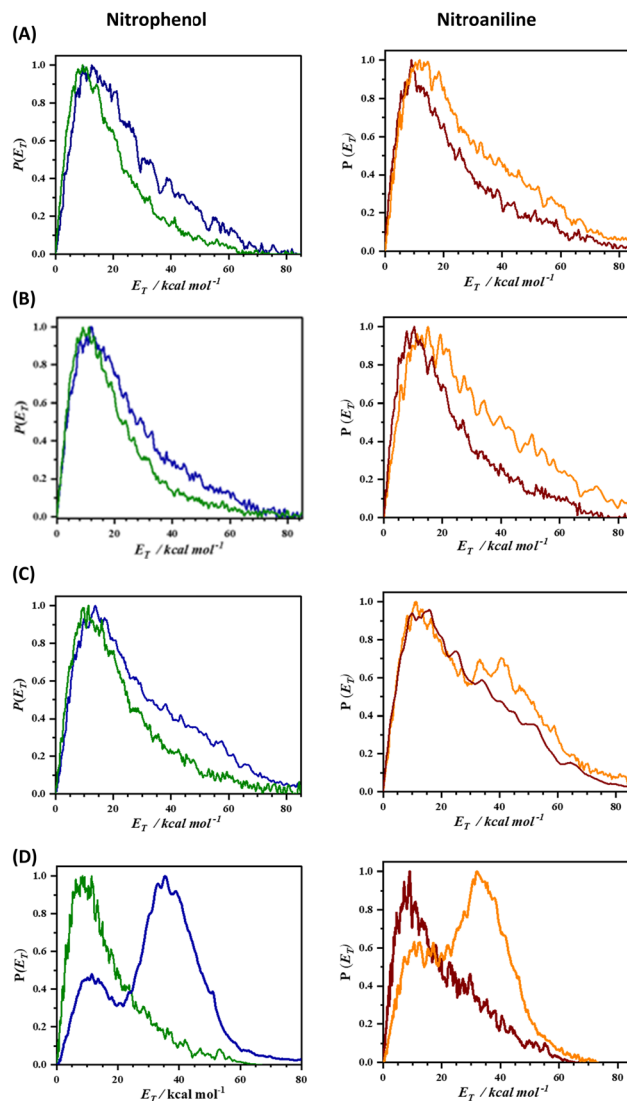


**Fig. 1** Two-dimensional potential energy surface (2D-PES) plots of *o*-nitrophenol, *m*-nitrophenol, *o*-nitroaniline, and *m*-nitroaniline calculated using the B3LYP/6-311++G(d,p) level of theory. The blue dashed lines represent the minimum energy paths (MEPs) connecting the starting structure (bottom right corner) with the formation of NO and the co-fragment phenoxy radical (top left corner) in the  $T_1$  state. The energy scale is in  $\text{kcal mol}^{-1}$  relative to the starting geometry on the  $T_1$  surface. The one-dimensional cut of the 2D-PES along the minimum energy path resulting in NO release is shown in Fig. S1 (ESI $^\dagger$ ) along with the selected geometries.

substituents, in the *ortho* position, capable of hydrogen bonding (OH and  $\text{NH}_2$ ), while in the other cases (H,  $\text{CH}_3$ ,  $\text{OCH}_3$  and  $\text{CF}_3$  groups), the NO release *via* an oxaziridine ring-type mechanism is preferred.<sup>8</sup> On the other hand, the variation in the substituents at the *para* position had only a marginal influence on the *s/f* branching ratio.<sup>9</sup>

A pertinent question that arises at this state is: does the intramolecular hydrogen bonding between the  $\text{NO}_2$  and the *ortho* substituent influence the NO release mechanism? To test this hypothesis 2D-PESs in the  $T_1$  state were calculated for two pairs of substituted nitrobenzenes in which the OH and  $\text{NH}_2$  groups were switched from the *ortho* position to the *meta* position and the corresponding 2D-PESs in the  $T_1$  state are shown in Fig. 1 and Fig. S2 (ESI $^\dagger$ ). These 2D-PESs clearly illustrate that the minimum energy path switches from the  $\text{NO}_2$  roaming mechanism to the oxaziridine ring-type mechanism for both OH and  $\text{NH}_2$  substituents when shifted from the *ortho* to *meta* position, respectively. The topographical aspects of the 2D-PESs remained unaltered with two distinct DFT functionals *viz.*, B3LYP and M06-2X (compare Fig. 1 and Fig. S2, ESI $^\dagger$ ). Since the 2D-PES is the projection of the multi-dimensional potential on two nascent internal coordinates leading to NO release, it can be therefore hypothesised based on the minimum energy pathway in the 2D-PESs that the *s/f* ratio will be higher in the *ortho* isomer in comparison with the *meta* isomer.<sup>8</sup>

The experimental realization of this conjecture based on the 2D-PES calculation was carried out by measuring the total



**Fig. 2** The total translational energy distribution profiles  $[P(E_T)]$  of NO, produced from nitrophenol (left panel) and nitroaniline (right panel), probed for various product states of NO ( $v = 0$ ;  $J = 21.5$ , (B)  $v = 0$ ;  $J = 29.5$ , (C)  $v = 0$ ;  $J = 33.5$  and (D)  $v = 1$ ;  $J = 50.5$ ). The  $[P(E_T)]$  profiles of the *ortho* and *meta* nitrophenols are depicted by solid green and blue curves, respectively, while *ortho* and *meta* nitroanilines are represented by solid brown and orange curves, respectively. It is noteworthy that the fast component in the  $[P(E_T)]$  profiles of *meta* isomers is consistently higher than that of the *ortho* isomer across all the product states.

translational energy distribution profiles of NO produced from *o*-nitrophenol, *m*-nitrophenol, *o*-nitroaniline, and *m*-nitroaniline using the velocity map imaging (VMI) technique<sup>10</sup> and the results are presented in Fig. 2. In all the four NO product states that were probed, the translational energy distribution profiles show bimodal behaviour (see Fig. S3 and S4, ESI $^\dagger$ ) with the *s/f* branching ratio for the *ortho* isomer higher than the corresponding *meta* isomer (see Table 1). Additionally, the *s/f* ratio of *o*-nitrophenol is always higher than the *o*-nitroaniline, which is in accordance with the fact that the OH group forms stronger hydrogen bonds than the  $\text{NH}_2$  group. These observations clearly reinforce the role of intramolecular hydrogen bonding in

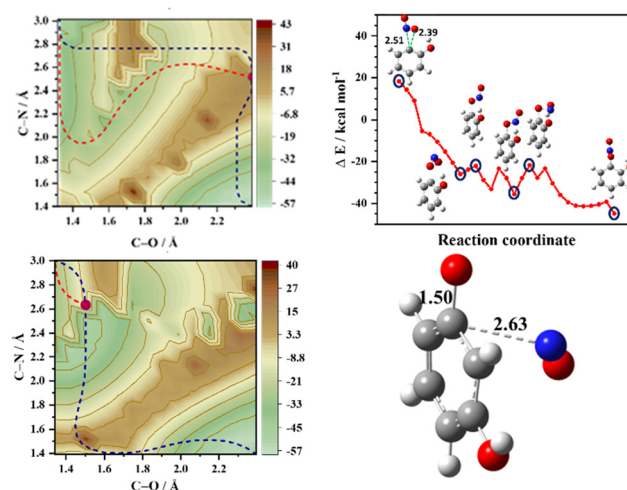
**Table 1** Slow-to-fast (*s/f*) branching ratios for various NO product states

NO product state	Nitrophenol		Nitroaniline	
	<i>ortho</i>	<i>meta</i>	<i>ortho</i>	<i>meta</i>
$\nu = 0; J = 21.5$	4.92	3.17	3.23	2.28
$\nu = 0; J = 29.5$	5.40	3.78	3.67	2.38
$\nu = 0; J = 33.5$	4.31	2.31	2.05	1.21
$\nu = 1; J = 50.5$	3.85	0.33	1.92	0.45

favouring the slow component. In general, the contribution from the fast component increases with rotational quantum number  $J$ , in agreement with the earlier reports;<sup>4</sup> however, this effect appears to be more prominent with an increase in vibrational quantum number  $\nu$ . It must be noted that the 2D-PES is a projection of the multidimensional potential in two-dimensions and hence a simplified model. The trends in the *s/f* branching ratio, therefore, are an indicator of the influence of the substituent to form intramolecular hydrogen bonding with the NO<sub>2</sub> group resulting in the enhancement of the roaming mechanism, thereby validating the initial hypothesis.

The topology of the T<sub>1</sub> surface regulates the preferential mechanism; however, it has been well established that the nature of the T<sub>1</sub>/S<sub>0</sub> crossing points and the exit barrier on the S<sub>0</sub> surface dictate the translational energy of the NO products.<sup>4,5,11–14</sup> In order to assess the role of the S<sub>0</sub> surface on the translational energy distribution of the NO products, 2D-PESs in the S<sub>0</sub> state were also computed, which are depicted in Fig. 3 (and Fig. S5, ESI†). In the case of *o*-nitrophenol, an early (closer to the reactant) T<sub>1</sub>/S<sub>0</sub> crossing point along the minimum energy path on the T<sub>1</sub> surface is a loose transition state, reflecting the NO<sub>2</sub> roaming mechanism. The NO<sub>2</sub> roaming and the oxaziridine mechanism are distinguished by evaluating the difference between the two N–O bonds, which is depicted in Fig. S6 (ESI†). The roaming path is characterized by a sudden and late change in the difference between two N–O bonds, whereas the oxaziridine pathway is more gradual. On the S<sub>0</sub> 2D-PES, the pathway for NO release is corrugated with an exit barrier of about 14 kcal mol<sup>−1</sup> (see Fig. 3) and the presence of several phenyl nitrite like intermediates, which ultimately result in slow NO release. Conversely, in the case of *m*-nitrophenol, a late (closer to the products) T<sub>1</sub>/S<sub>0</sub> crossing point was observed along the minimum energy path on the T<sub>1</sub> surface, which leads to the fast translational energy component. The slow translational energy component of the NO release is generally attributed to the dynamics on the S<sub>0</sub> surface, which once again originates from the roaming and non-roaming mechanisms. Therefore, based on the present set of results, it can be inferred that intramolecular hydrogen bonding between the NO<sub>2</sub> and the substituent in the *ortho* position plays a pivotal role in enhancing the roaming mechanism, thereby resulting in a higher *s/f* ratio for the *ortho* isomer relative to the *meta* isomer as well as higher *s/f* ratio for the *o*-nitrophenol in comparison with *o*-nitroaniline.

Summarising, the branching ratio of the slow-to-fast (*s/f*) translational energy components, for various NO product states, shows a higher value for the *ortho* isomer in comparison to the *meta* isomer. Furthermore, consistently higher *s/f* ratio



**Fig. 3** Ground state (S<sub>0</sub>) 2D-PES plots of *o*-nitrophenol (top left) and *m*-nitrophenol (bottom left) with the projected minimum energy path (MEP) that connects the reactant (bottom right corner) to the NO and phenoxy radical as products (top left corner) in the T<sub>1</sub> state (blue dashed line). The purple dot represents the T<sub>1</sub>/S<sub>0</sub> crossing point along the T<sub>1</sub> MEP and the red dashed lines represent the MEPS in the S<sub>0</sub> state. Note that the T<sub>1</sub>/S<sub>0</sub> crossing for *o*-nitrophenol and *m*-nitrophenol is early and late relative to the reactant, respectively. The S<sub>0</sub>-MEP and selected structures after the T<sub>1</sub>/S<sub>0</sub> crossing point for *o*-nitrophenol are shown (top right) along with the T<sub>1</sub>/S<sub>0</sub> crossing point of *m*-nitrophenol (bottom right). The distances are shown in Å and the energy scale is in kcal mol<sup>−1</sup> relative to the starting geometry in the T<sub>1</sub> state.

for the *o*-nitrophenol over *o*-nitroaniline is attributed to the OH group's propensity to form stronger hydrogen bonds compared to the NH<sub>2</sub> group. Therefore, it is inferred that the *ortho* isomer preferentially releases the slower NO fragments, which is attributed to the minimum energy roaming path. On the other hand, in the *meta* isomers, the faster component mediated *via* the oxaziridine pathway is enhanced. Thus, it has been illustrated that the hydrogen bonding ability of the substituent in the *ortho* position to the NO<sub>2</sub> group favours the roaming mechanism.

A skimmed molecular beam of helium doped with the heated (330–350 K) reagents (*o*-nitrophenol, *m*-nitrophenol, *o*-nitroaniline, and *m*-nitroaniline; Sigma Aldrich) was intersected by a counter-propagating pump (266 nm) and probe lasers<sup>15</sup> and the ensuing NO cations were detected *via* the A<sup>2</sup>Π – (X<sup>2</sup>Π) [(0,0); Q<sub>1</sub> (J = 21.5; 29.5; 33.5)] and A<sup>2</sup>Π – (X<sup>2</sup>Π) [(1,0); P<sub>1</sub> J = 50.5]<sup>16,17</sup> and imaged. Each image was collected for 50 000 shots, which were symmetrized using ImageJ software.<sup>18</sup> Abel inversion was carried out by the Basis Set Expansion method (BASEX) to extract the translational energy distribution.<sup>19</sup> The plane of polarization of both lasers is kept parallel to the plane of the detector and the laser flux was optimized such that the signal intensity for the NO fragment was observed only in the presence of both the pump and probe lasers. The total translational energy profiles [P(E<sub>T</sub>)], black traces in Fig. S3 and S4 (ESI†), were fitted to a bimodal empirical function,<sup>8,20,21</sup>

$$P(E_T) = C \cdot [(E_T)^{a_1} \cdot (E_T^{\max} - E_T)^{b_1} + (E_T)^{a_2} \cdot (E_T^{\max} - E_T)^{b_2}]$$

where  $a_1$ ,  $a_2$ ,  $b_1$ , and  $b_2$  are adjustable parameters,  $C$  is a normalization constant, and  $E_T^{\max}$  is the maximum total

translational kinetic energy available for the fragments in the centre-of-mass frame after dissociation.

The experimental results were interpreted by calculating the two-dimensional potential energy surfaces (2D-PES) in the ground ( $S_0$ ) and first excited triplet ( $T_1$ ) states with the B3LYP/6-311++G(d,p) and M06-2X/6-311++G(d,p) levels of theory using the Gaussian 09 suite of programs.<sup>22</sup> The 2D-PESs were mapped along two internal coordinates; the C–N bond (“C” referring to the carbon atom of the aromatic ring to which the nitrogen atom “N” of the nitro group is attached) and C–O bond (“O” referring to the oxygen atom of the nitro group that is away from the *ortho* substitution, which later forms a bond with the “C” atom of the aromatic ring leading to NO release). The distances  $R_{(C-N)}$  and  $R_{(C-O)}$  are varied in the range 1.4 to 3.0 Å and 1.25 to 2.3 Å, respectively, in 14 equidistant steps on each coordinate resulting in 196 data points. The minimum energy path on the 2D-PES for the release of NO from each of the substituted nitrobenzenes was evaluated using the Minimum Energy Path Surface Analysis (MEPSA) tool.<sup>23</sup>

PRC thanks PMRF for the research fellowship and MK is supported by the Women Scientists Scheme of the Department of Science and Technology (Grant no. SR/WOS-A/CS-18/2019). Financial support from the Science and Engineering Research Board of the Department of Science and Technology (Grant no. CRG/2022/005470) and the Board of Research in Nuclear Sciences (BRNS Grant no. 58/14/18/2020) is gratefully acknowledged. The authors wish to thank Ms Shaivi Kesari and Ms Bhawana for their help in carrying out some of the experiments. GNP wishes to thank Kaleidoscope-2023 for stimulating discussions.

## Conflicts of interest

The authors declare no conflict of interest.

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